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"Deformation History, Fluid Flow Reconstruction and Reservoir Appraisal in Foreland Fold and Thrust Belts"
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Evidence for Squeegee Flow in the Rocky Mountain Foreland Basin

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INTRODUCTION

The Alberta Basin in western Canada contains four regionally extensive Devonian aquifers and hydrocarbon reservoir levels, traditionally called D1-D4. Due to the asymmetry of the basin, these strata subcrop or crop out near the northeastern limit of the basin and dip southwestward to depths of about 6 km close to the limit of the disturbed belt, which originated during the Laramide orogeny that formed the Rocky Mountains in the Late Cretaceous to Early Tertiary. Within the study area (stippled outline in Fig. 1), the Devonian strata lie at depths of 2-5 km with an average slope of about 1 degree, and consists mainly of marine carbonates and shales, approximately 1 km in thickness. Across much of the basin the four Devonian aquifers are interbedded with marl and evaporite aquitards, confined by tight evaporites at the base and by shales at the top.

Central to this study is a prominent feature in the deep part of the basin, the Southesk-Cairn Complex (SCC). This complex is a major Upper Devonian (D2+D3), northeast to southwest-trending platform-reef sequence that extends 125 to 150 km into the foreland basin from the limit of the disturbed belt. Palinspastic restoration of exposures in the Rocky Mountains extends the complex about 300 km farther to the southwest (Fig. 1). We investigated the SCC mainly in the subsurface but also in some outcrops.

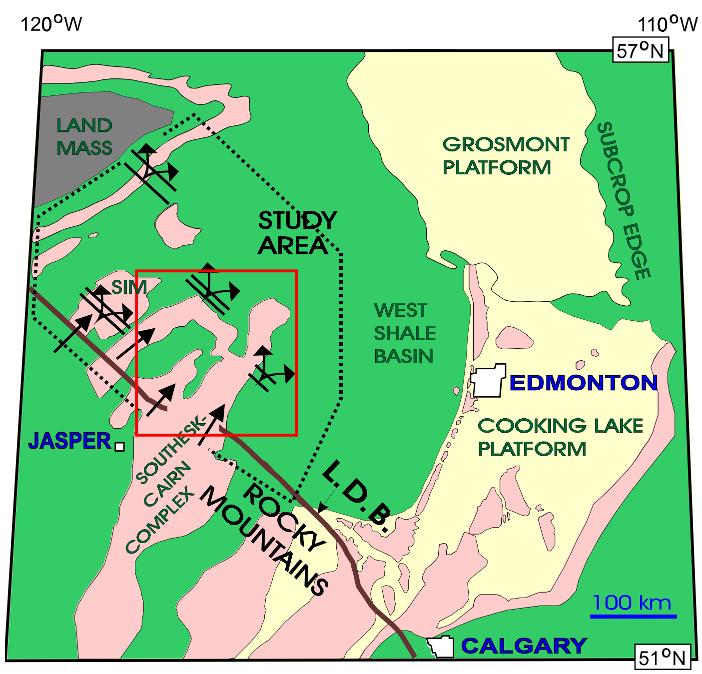

Figure 1. Devonian platform and reef carbonates of the Late Devonian Woodbend Group (D3) in the Alberta Basin. Light grey pattern: undifferentiated Cooking Lake and/or Leduc Formations and their outcrop equivalents; medium grey pattern: reef complexes; darkest grey: basinal areas. Fat double lines denote fault systems; black arrows mark inferred paleofluid flow, as explained in the text. L.D.B. = limit of the disturbed belt. SIM = Simonette. The outline of the overall study area is stippled. The inserted box northeast of Jasper marks the outline of the map shown in Figure 2.

The major objective of this study is to investigate whether tectonic expulsion of formation fluids *sensu* the so-called "squeegee model" (Oliver 1986) can be identified and/or characterized in the deep part of the Alberta Basin. To this end, we are investigating chemical as well as physical components of the present and (inferred) past fluid flow.

RELEVANT ASPECTS OF STRATIGRAPHY

Stratigraphic investigations and correlations, using well logs and drill core, show that the Devonian strata consists of carbonate aquifers with interbedded marls and evaporites. The aquitards, although generally regionally continuous, are thin or missing in the deepest part of the basin, such that the four aquifers form a thick, contiguous "mega-aquifer" near the limit of the disturbed belt. Furthermore, the aquitards are locally discontinuous and/or relatively permeable where thinner than about 10m, which leads to cross-formational flow of water and/or hydrocarbons in some locations.

RELEVANT PARAGENETIC AND GEOCHEMICAL DATA

Most rocks of the SCC are medium to coarse-crystalline, grey dolostones with poorly preserved primary textures. These dolostones are similar to those that are common elsewhere in the basin, and that probably formed from some type of pervasive convection of chemically modified seawater at depths of about 500 to 1,500m (e.g., Mountjoy et al. 1999). Most oil and gas is contained in molds and vugs that formed during or after pervasive dolomitization. Several other diagenetic phases, including early marine calcite cements and traces of bacteriogenic sulfide, are common but not abundant. Most important in the present context are coarse-crystalline white calcite cements that occur in overall volumes of about 1 - 2 %, and that, like the hydrocarbons, occur in dissolution vugs.

The stable isotope data of white calcite cement from the SCC show a wide range in $\delta^{13}C$ (ca. 0 to -27 ‰ PDB) over a small range of $\delta^{18}O$ (ca. -7 to -12 ‰ PDB). The range of $\delta^{13}C$ indicates incorporation of variable amounts of isotopically light carbon derived from the oxidation of organic carbon. Considering that these particular samples were retrieved from sour gas fields that probably have never been in contact with meteoric water, thermochemical sulfate reduction (TSR) is the only realistic interpretation for these $\delta^{13}C$-data.

Most of the $^{87}Sr/^{86}Sr$-ratios of late calcite cements from the SCC in the subsurface are well above the Middle- to Upper Devonian seawater value of about 0.7085 and also above *MASIRBAS*=0.7120. The latter value is the “Maximum Sr Isotope Ratio of Basinal Shales”, as determined by Sr-leaching experiments (Machel and Cavell 1999) that the formation waters can obtain by circulation through these shales at diagenetic temperatures. Values higher than *MASIRBAS* indicate a metamorphic origin of at least some Sr. Furthermore, the $^{87}Sr/^{86}Sr$-ratios of these calcites are not randomly distributed. Rather, they are highest near the limit of the disturbed belt, 0.7323, and generally decrease northeastward to about 0.7132 (Fig. 2).

These findings suggests a source of Sr from the fold and thrust belt, as well as a generally northeasterly flow from the Rocky Mountains into the foreland basin, while these particular calcites formed. Furthermore, such fluid flow probably was not restricted to the SCC. The highest values measured to date are from the Simonette reef just north of the SCC (Figures 1, 2), where late calcites range up to 0.7370 and late dolomites range up to 0.7369.

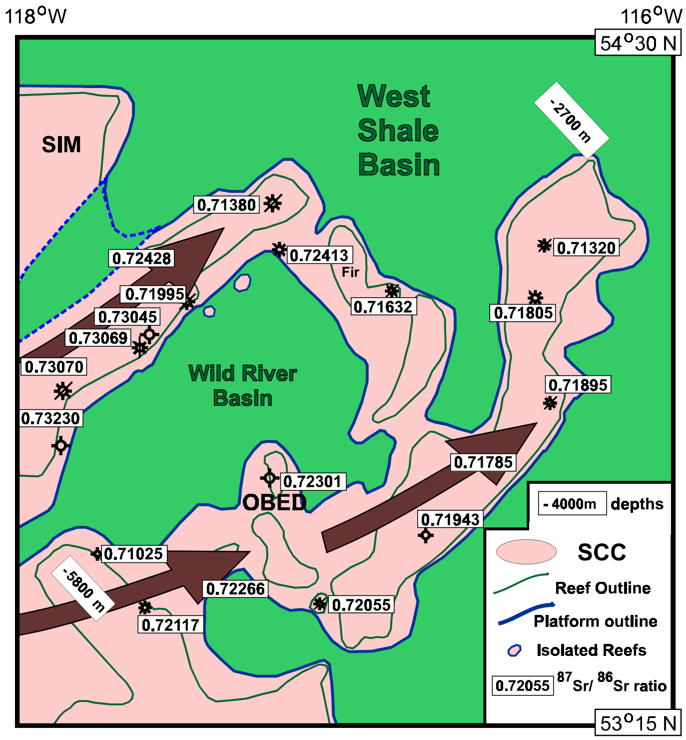

Figure 2. Distribution of Sr-isotope values of late calcite cements in the Southesk Cairn Complex northeast of Jasper. See Figure 1 for location of this map. The outline of the D3 platform is much more lobate than shown in the overview map of Figure 1. Seismic data are ambiguous in the northwest, i.e., the Simonette Reef (SIM) may or may not be connected to the SCC proper. Arrows denote inferred flow of ^{87}Sr-enriched fluids.

The paragenetic sequences established for various parts of the SCC place the white calcite cements as the youngest events of lengthy diagenetic histories. Fluid inclusion data for some of these samples indicate crystallization temperatures ranging from 130 to 160°C, the same range at which TSR is inferred to occur. However, the fluid inclusion data do not show a regional northeastward trend comparable to that of the Sr-isotope data.

PRESENT HYDROGEOLOGY

Formation water chemistry and pressure data from standard drillstem tests were used to interpret the present flow conditions within the four Devonian aquifers. Formation water salinity and geothermal gradients were used to calculate water density. Maps of salinity, density and hydraulic head distributions were used in the flow analysis.

The salinity and bicarbonate distributions suggest the existence of two different brines in the investigated Devonian aquifers. A lower-salinity brine (100-175 g/l) fills the pore spaces in the south and along the deformation front, downdip from a high-salinity brine (200-300 g/l). The low-salinity brine has a high bicarbonate content (750- 4000 mg/l). The transition zone between the two brines is characterized by relatively sharp salinity gradients. Generally, the heavier brine is located progressively farther updip.

Impelling forces acting on formation waters in each aquifer were calculated based on hydraulic-head and density distributions, to account for both potential and buoyancy components. The force vectors indicate regional-scale converging flow directions for the two brines, with the lighter brine moving updip and laterally, similar to the arrows shown for paleofluid flow in Figure 2. Both types of brines are interpreted to be of mainly 'connate' origin, their high salinity being the result of seawater evaporation during the Devonian and some mixing with Laramide to Pliocene meteoric waters.

CONCLUSIONS

Our data indicate that the source of the elevated $^{87}Sr/^{86}Sr$-ratios in the deepest part of the Southesk-Cairn complex is most probably fluids that interacted with and/or were derived from metasedimentary Precambrian rocks. One likely possibility is the Proterozoic Miette Group, which is present in outcrop near Jasper and extends at depth along the entire eastern front of the Rocky Mountains. The overall small amounts of the white calcite cements (1- 2 vol-%) reflect a relatively small volume of fluid from an external source flowing through a limited rock system during or immediately after TSR. The spatial distribution of the $^{87}Sr/^{86}Sr$-ratios suggests a general northeastward flow through the Southesk-Cairn complex, with $^{87}Sr/^{86}Sr$-ratios in the fluids decreasing northeastward because of dilution and increasing water-rock interaction with the host carbonates.

These findings are strong evidence for squeegee-type flow in the Southesk-Cairn Complex, whereby fluids were expelled laterally into the adjoining carbonate aquifer(s) via thrust sheets and/or from Precambrian basement metasediments via faults that transect the underlying Cambrian clastics. The present flow system and salinity distribution in the deep part of the basin may reflect, at least in part, past squeegee flow. Our data further suggest that squeegee-type flow was laterally rather limited, extending perhaps only 100 to 200 km into the foreland basins, where the radiogenic Sr signal "disappears". Our data, therefore, support the results of modeling studies that indicate generally low fluxes for squeegee flow.

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